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6. AUTHOR(S)
Dr Jain

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of New Mexico
Scholes Hall 102
Albuquerque NM 87131-6003

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3. Development of diode pumps for nonlinear conversion.

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Final Technical Report ***(31 Aug 94 - 30 Aug 97)***

Efficient Near and Mid-Infrared Dielectric Waveguide Lasers

The development of mid-IR and near-IR waveguide lasers for spectroscopic applications was pursued in this project via a multi-pronged approach, consisting of parallel part-time efforts in several different complementary areas, namely:

1. Research and development of mid-IR fiber laser sources
2. Mid-IR sources by nonlinear mixing/OPOs based on quasi-phasematched (QPM) waveguides
3. Development of diode pumps for nonlinear conversion

I. Research and development of mid-IR fiber laser sources

We have achieved relatively high output powers and operating efficiencies from a continuous wave 2.7 μm double-clad Er:ZBLAN fiber laser, whose output powers should be scalable to the Watt power level with commercially available 780 nm diode pumps. In particular, we have demonstrated ~40 mW output powers using a 780 nm $Ti:Al_2O_3$ laser pump. We have also achieved diode-pumped operation, with ~10 mW output power levels at 2.7 μm using a readily available 980 nm pump. As such, this work represents the first report of the use of a double-clad fiber for a mid-IR fiber laser.

Figure 1 shows the basic experimental arrangement used in this work. The choice of the 5.5 m long double clad fiber was based on our plans to replace the currently-used pump laser with high power diode pumps of relatively low beam quality. Results based on two different pump sources are discussed below.

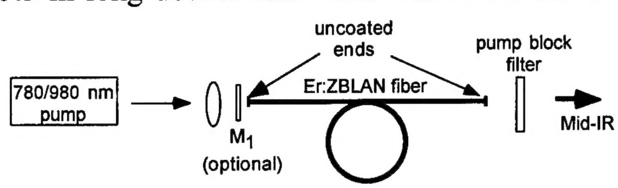

Fig 1. Schematic of the Er:ZBLAN fiber laser

In the first experiment, we used a 1 Watt 980 nm laser diode based on a tapered amplifier structure[6]. At the input end, an HR mirror (M_1) was butt-coupled to the fiber while the cleaved distal end was used as a 96% output coupler. The output power from the fiber laser was monitored by completely attenuating the 780 nm pump with a 2.7 μm (T=90%) transmitting filter. Figure 2 shows the 2.7 μm output power as a function of launched pump power. The low lasing threshold of 30 mW for a 96% output coupler, and the fact that no saturation of the output power is observed even at the highest pump powers used indicates that this 980 nm pumped laser can be further optimized to yield much higher output powers.

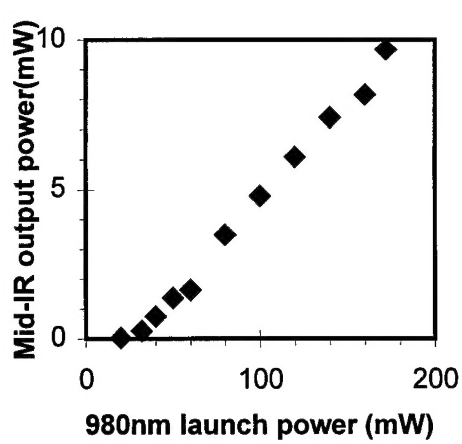

Figure 2. P_{out} vs P_{in} for 980 nm diode pump

In the second experiment, we used a 780 nm $Ti:Al_2O_3$ pump and a simple cavity design comprising of the 4% Fresnel reflections at the two uncoated fiber ends. Note that for the data reported here, mirror M_1 (shown in Fig 1) was not used. A key feature of the work reported here is the use of a pump wavelength of 780 nm

(compared to the 791 nm pump wavelength used previously for excitation of the $^4I_{11/2}$ upper laser level via the $^4I_{9/2}$ pathway); this choice of pump wavelength is demonstrated to be approximately 3 times more efficient than the use of a 791 nm pump in our laser design, as elaborated below.

Figure 3 shows the P_{out} vs. P_{in} curve for this fiber laser when pumped by 780 nm single transverse mode Ti:Sapphire pump radiation that is directly coupled to the fiber core (coupling efficiency ~50%) corresponding to its current use as a simple "single clad" fiber. The vertical axis in Fig 3 corresponds to mid-IR power output from both ends of the fiber laser, and lasing threshold corresponds to a gain of 5.85 dB/round-trip at a pump power of ~25 mW corresponding to a pump power density of ~400 KW/cm^2. Note that even at the highest pump power levels, there is no evidence of saturation of the output power from this 2.7 μm fiber laser. As such, in a follow-on experiment currently in progress, comparable gains should be attainable with the use of ~20 W of diode pump power (Optopower Corp.) coupled partially into the core and partially into the diode-pump confining inner cladding; for this experiment, output power levels of the order of a Watt are anticipated.

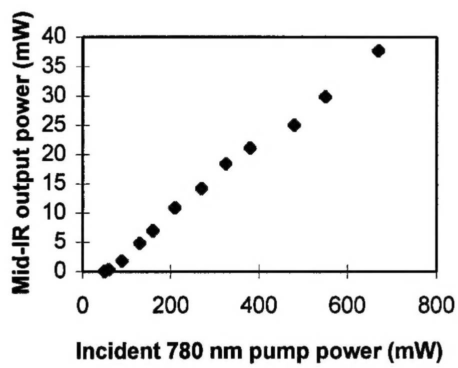

Figure 3. P_{out} vs. P_{in} for 780 nm Ti:S pump

Figure 4 shows the "excitation spectrum" of such a fiber laser corresponding to a constant incident pump power of 600 mW. Note that in contrast to a previous report[2] on the output power of such a mid-IR fiber laser as a function of the pump wavelength, in our work 3 times greater output power was obtained with the use of the 780 nm excitation wavelength when compared to the use of the more traditional 791 nm pump wavelength[2-4], despite the higher ground state ($^4I_{15/2}$ to $^4I_{9/2}$) absorption at 791 nm. We are studying this effect in detail, and we currently ascribe the observed behavior to reduction in ground state bleaching effects[7], as well as to the reduction of deleterious effects caused by significantly lower ESA[5,8] (from the upper laser level $^4I_{11/2}$ to $^4F_{5/2}$) for 780 nm, and the wavelength dependence of the "beneficial" lower-level ($^4I_{13/2}$) depleting ESA to the $^4H_{11/2}$ level[5,8].

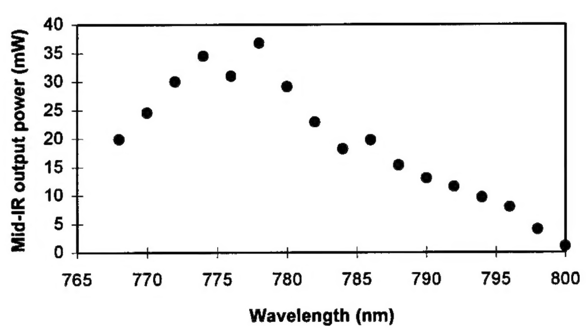

Fig 4. Excitation spectrum for 2.7 μm laser

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II. Mid-IR sources by nonlinear mixing/OPOs based on QPM waveguides

We plan to use tunable, narrow linewidth high power tapered amplifier diode lasers for nonlinear downconversion to mid-infrared wavelengths using quasi-phasematched PPLN (Periodically Poled Lithium Niobate) structures (for additional details see Section III below)

III. Development of diode pumps for nonlinear conversion

High peak power diode lasers are very desirable for several applications including efficient generation of mid-IR wavelengths by nonlinear mixing in QPM-PPLN structures. We report detailed results on the gain switching operation of a practical monolithic two section laser diode. Our preliminary results [i] on the performance of this device operated in a external cavity showed high power (~1.2 W, <100 ps FWHM) optical pulses, in this letter we examine another variety of short pulse generation using the same device. This structure uses a narrow ridge gain section combined with a tapered gain section within a common optical cavity that allows independent modulation of the two sections. This structure combines the good beam quality of the tapered amplifier structures with ease of modulation of the narrow stripe configuration. The narrow ridge acts as a single mode waveguide providing spatial filtering of the laser's mode, as well as allowing high frequency modulation due to its small junction capacitance and low threshold current. The tapered section provides a gain region for high power operation, preserves mode quality by accommodating adiabatic expansion of the beam, and minimizes facet degradation by having a large output area. This device combines a number of attractive features that offer exciting prospects.

Some high power laser diodes use narrow stripe lasers, which produce good quality beams but are usually limited in power due to output facet thermal damage. Alternatively, broad area edge emitting lasers can produce high output powers at the expense of lateral beam quality. The best results so far have been obtained through the use of tapered devices [ii,iii] which allow for lateral adiabatic expansion of the beam, thus providing good lateral beam quality while minimizing facet damage with a large output facet area. The approaches to short pulse generation in these devices include mode-locking [iv] or gain switching [v] a narrow stripe and tapered amplifier compound laser, Q-switching a bow-tie laser with tapered amplifier [vi], and gain switching a tapered stripe laser diode [vii]. Monolithic structures are inherently simpler than compound cavity or master oscillator traveling wave amplifier structures since there is no need for additional coupling optics.

Our two-section device has demonstrated a significant improvement in pulse energy over previously reported monolithic devices. We have shown ~200 pJ pulse energies which can be compared to other monolithic devices: 100 pJ for the Q-switched bow tie laser [viii], 59 pJ for the gain switched tapered stripe[vii], and 10 pJ for Q-switched three contact devices [ix].

For the two section device, we have defined the ridge threshold (28 mA) and taper threshold (700 mA) as the minimum currents necessary for each section to allow the entire

device to achieve continuous wave oscillation. If either section is biased below its threshold, oscillation will not occur because the cavity spoiling grooves prevent oscillation unless both sections provide gain. The means of gain switching this two section device is to provide the tapered section with a continuous current at a level above its threshold, to provide gain for that section. The ridge section is biased slightly below its threshold and modulated with short duration electrical pulses which bring it far above its threshold. The carrier density in the ridge section rises so fast that when it exceeds the threshold level there is significant overshoot before the photon density (light pulse) rises and consumes the excess carriers. The effect of the tapered section is to make more carriers available without imposing the requirement of rapid modulation. This results in higher pulse energies.

The two section laser diode (see Figure 5) is a InGaAs/AlGaAs graded index separate confinement heterostructure (GRINSCH) structure. The device is mounted p-side down onto a diamond heat sink with a patterned metalization which provides electrical isolation so that separate electrical contacts can be made to each of the two sections. Also the metalization on the p-side of the wafer is patterned and the two metal contacts are separated by a shallow etch to remove the p+ contact layer between them. This provides electrical isolation. A separate electrical connection is made to the common substrate side of each of the two sections to minimize crosstalk between the ridge modulation circuitry and the taper bias circuitry which otherwise might occur when current from one section flows through a resistive path that is common to both sections. The ridge section is a single mode waveguide that is 2 μm wide and 1000 μm long. It acts to spatially filter the transverse mode. The tapered section is 2 μm wide at the end near the ridge section and tapers with a 3° half angle to 210 μm at the output facet. The laser cavity was formed by using the Fresnel reflections from the SiO_2 passivated cleaves on the back of the ridge section and the front of the tapered section. In order to prevent the formation of a laser cavity that does not include the ridge waveguide, there is an angled etch on either side of where the ridge section meets the tapered section. This cavity spoiling etch acts to scatter light away from the longitudinal axis of the structure, and also out of the GRINSCH waveguide. This will spoil the parasitic Fabry-Perot laser cavity that does not require guiding by the ridge waveguide. This etch allows operation of the tapered section at high currents while still maintaining the ability to modulate the device output with the ridge current.

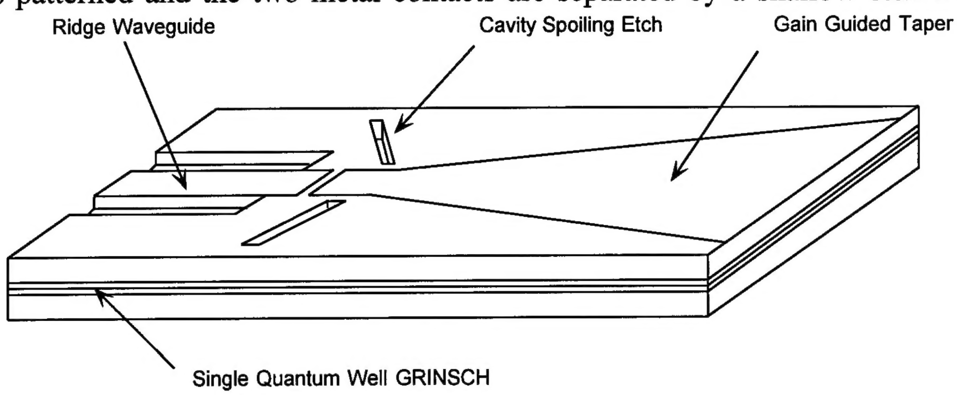

Figure 5. Two Section Device Structure

The ridge section was modulated with short (~200 ps) high amplitude (~7 V peak into 50 Ω) electrical pulses generated by a comb generator and pulse inverting transformer. The comb generator was driven by an amplified radio frequency synthesizer at 320 MHz. The short pulse modulation was biased by a precision direct current source through a bias-T, then was sent to a 47Ω impedance matching resistor and to the ridge section. The tapered section was driven by a direct current of 800-1200 mA provided by a laser diode controller, which also maintained the

entire structure at 20.5°C through the use of a thermoelectric cooler. The output of the diode laser was collimated and fed into a 22 GHz bandwidth, high speed, fiber coupled, detector with a 20 GHz amplifier. The resulting signal was observed on a sampling oscilloscope, and pulse full-width-half-maximum durations were determined.

For each bias condition, the average power was measured with and without radio frequency modulation. The difference between the two power measurements corresponds to the average power contained in the pulses. Using the FWHM duration of the pulses and the pulse repetition frequency (320 MHz) the duty cycle, peak power, and pulse energy were calculated (see Figure 6). The falloff of the pulse energies at higher ridge biases is due to the consumption of available carriers by a continuous wave component of the output. At taper currents of greater than 1200 mA a satellite pulse began to form which made calculation of peak powers and pulse energies unreliable.

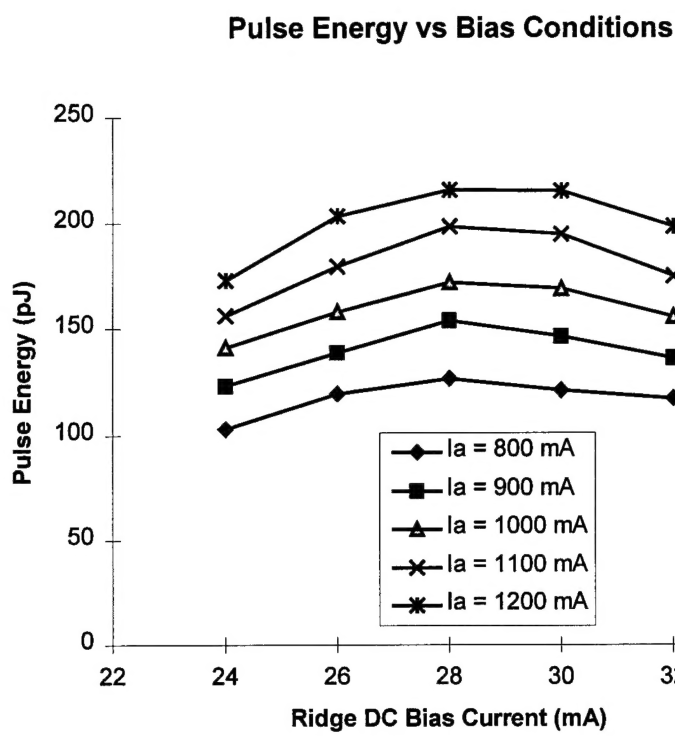

Figure 6. Pulse Energy vs. DC Bias in Ridge for Various Taper Currents (Ia)

The best results were achieved when the ridge section was biased just above its threshold (30 mA) and the tapered section was biased to just below the point of satellite pulse/pedestal formation (1200 mA.) Under these conditions we measured 140 ps FWHM pulses at 320 MHz repetition rate, with >1.5 Watts peak power. The shortest duration pulses observed were 130 ps long.

It has come to our attention that independent parallel work [x] on gain switching a similar device has recently been published. The two section device we demonstrate is similar in design, however its larger area provides a factor of ten improvement of pulse energy, and the parasitic cavity spoiling etches present in our design allow operation of the taper section at much higher currents without overriding the effect of the ridge section.

In summary, we have demonstrated a practical two section strained quantum well diode laser that enables the generation of high peak power (>1.5 W), high energy (>200 pJ), short duration (<135 ps) gain switched pulses.

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The University of New Mexico
Center for High Technology Materials
1313 Goddard SE
Albuquerque, NM 87106
Office Hours:
8 am - 12N and 1 pm - 5 pm Mountain Time

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Office: (505) 272-7800
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